# Ulysses Above the Sun's South Pole: An Introduction

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Between June and November 1994, the field and charged particle environment of the sun above 70" latitude was surveyed for the first time. This general introduction sets the stage for the accompanying articles which present the first scientific results obtained at high solar latitudes. The trajectory, the spacecraft, the experiments and the scientific background of the mission are described briefly. Several of the major scientific highlights are then summarized. The solar wind speed has been found to be nearly constant above 50° latitude and the flow is much smoother than near the sun's equator. The relative abundances of heavy ions have revealed compositional differences between slow (low latitude) and fast (high latitude) solar wind. The radial magnetic field component has not changed with latitude implying that the stronger polar cap magnetic fields are being transported equatorward and are influencing the solar wind flow in the extended corona. Galactic cosmic rays have failed to exhibit a significant increase in intensity with latitude. Their access to the polar regions is apparently being opposed by outward-traveling, large amplitude waves in the magnetic field that have been found to be continuously present at high latitudes.

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The international Ulysses mission is a joint undertaking of the American and European Space Agencies (1). The spacecraft was designed, built, tested and is being operated under the direction of the European Space Agency (ES A). NASA was responsible for the launch and is acquiring the data with the antennas of the Deep Space Net. Scientists both in Europe and in the U.S. supplied the experiments and are interpreting the results.

The spacecraft is following a unique trajectory which allows it to escape the confines of the solar equator, where all measurements had been made previously, to reach the vicinity of the sun's poles. Figure 1 is an overview of the flight path with key dates identified. The spacecraft was launched over 4 years ago, on 6 October 1990, using the space shuttle and three upper stages to escape the earth at high speed enroute to Jupiter. A gravity assist by the planetary giant was needed to overcome the severe limitations of launching from the moving Earth as it travels around the sun's equator at a speed of 30 km/sec. The first leg of the journey followed an ellipse which lay near the ecliptic plane (the plane of the Earth's orbit around the sun) leading to an encounter with Jupiter. The encounter on 11 February 1992, changed the orbit into an ellipse inclined 80° to the solar equator. The spacecraft is now following a path that takes it under the sun (or above the south polar cap) first, because that is energetically favored, then returns to the ecliptic (March 1995) and passes over the north pole (June-September 1995 ).

The heliographic latitude and radial distance of Ulysses near the sun's south pole are shown in figure 2. The maximum latitude of 80,22° was reached on Day 256 (13 September) 1994. The radial distance at that time was 2.29 A.U. (Astronomical Unit, the average distance of earth from the sun). Latitude and distance are plotted both as a function of day of year (top) and by month (bottom) since the accompanying articles may use either in presenting the observations.

Figure 3 is a drawing of the spacecraft which spins about the. center line of the high gain antenna at a rate of 5 rev/min. Several long appendage.s extend from the spacecraft body, a dog-leg boom containing four experiment sensors, two long wires which form an experiment antenna 72 meters long and a third wire antenna (7.5m long) deployed opposite to the high gain antenna. Other experiment sensors and all the spacecraft and experiment electronics are located around or within the main body. A tape recorder stores scientific measurements for -16 hours per day which are then played back along with interleaved real time measurements during the remaining -8 hours to provide continuous data coverage. Electrical power is supplied by two Radioisotope Thermoelectric Generators (RTGs) which protrude from the spacecraft opposite to the experiment boom.

Table I is a listing of the scientific investigations, their acronyms, the names of the Principal Investigators, and their institutions. Several Interdisciplinary Science Investigations are also included on Ulysses as shown in "l'able II. Numerous (-150) scientific co-investigators from America and Europe are also important participants. The experiments are providing comprehensive measurements of essentially all the fields and particles of scientific interest without gaps in energy or frequency coverage. The quality of the scientific information being obtained is equal to, or better than, the best measurements available in the ecliptic.

The Sun's outer atmosphere (2), which is normally visible only at times of eclipses, consists of two distinct regions, a narrow "ring" (the chromosphere) lying just above the solar surface (the photosphere) and a more extended highly structured upper atmosphere, (the corona). Chromosphere and corona result from a large increase in temperature above the visible disk caused by a poorly understood but non-radiative heat source. At the high temperatures and low densities in these regions, the solar gas is completely ionized consisting solely of electrons and the electrically-charged atoms (ions) from which they have been removed. This fully ionized gas (or plasma) consists principally of hydrogen and helium, the most abundant solar elements, with lesser abundances of heavier elements such as magnesium, oxygen and neon. The plasma is so hot that even the sun's enormous gravitational field cannot restrain it from flowing out into space. A conversion of random thermal motion into directed motion, analogous to that occurring in a rocket engine, causes the high speed solar wind,

The sun, like most planets and other stars, is magnetized, Electrical currents inside these bodies produce magnetic fields which extend upward through the surface and into the atmosphere. Very intense magnetic fields penetrating the surface as sunspots are restricted to a belt circling the sun within 30° of the equator. A weaker global field is also present with magnetic poles of opposite sign in the two polar regions. ‘I<he solar magnetic field undergoes major changes every eleven years, the number of sunspots waxing and waning and the polar field vanishing and then reversing sign, with corresponding changes in the solar wind and solar activity. The sun is now approaching sunspot minimum.

The large scale structure of the corona is imposed by the magnetic fields which are present in two very different forms. Near the equator, the magnetic lines of force begin and end in the photosphere and form loops (closed field lines). These field lines are customarily stretched out to form visible coronal structures called streamers. The tension of the closed field lines can help the gravitational field restrain the coronal plasma, One consequence is that solar wind flow near the streamers tends to be slow. Another consequence is that, occasionally, a body of plasma in the streamer overcomes this magnetic restraint and escapes as a Coronal Mass Ejection. Such events are characteristically accompanied by the emission of energetic particles and radio waves. At higher latitudes, the field lines can have one end on the sun with the other end extending radially outward (open field lines). In open field line regions, the plasma can flow into space continuously to produce fast solar wind. The lower density that results as the matter streams outward causes depleted dark regions called Coronal Holes.

The sun's magnetic poles represent an axis of symmetry that is inclined relative to the solar rotation axis. As the sun rotates, the solar wind in the ecliptic alternately comes from low and high magnetic latitudes and the speed varies from low to high values. Before reaching the orbit of earth, the high speed wind overtakes the slower wind and compresses it to form regions of piled-up magnetized plasma (Corotating Interaction Regions). This interaction can lead to the generation of collisionless shocks and the local acceleration of particles to high energies.

After leaving the sun, the solar wind expands to fill the solar system and pushes the nearby interstellar plasma outward to an estimated distance of= 100 AU. The enormous volume that is formed is called the heliosphere (3). The interstellar gas is only partially ionized and its neutral component (mostly hydrogen and helium) is unaffected by the solar wind and can enter the heliosphere. As these atoms approach the sun, they become ionized (positively charged) and are then picked up by the magnetic field in the outflowing solar wind. A substantial fraction of these ions of interstellar origin is subsequently accelerated to high energies in the outer heliosphere to form Anomalous Cosmic Rays. Also present in interstellar space are galactic cosmic rays, atomic nuclei accelerated to relativistic speeds in distant cataclysmic events, which can enter the heliosphere before being strongly affected by the solar wind magnetic fields. Interstellar dust is also able to penetrate into the heliosphere.

This brief description of solar-heliospheric physics is intended to clarify the scientific objectives of the mission and the following summary of the recent observations. A major objective has been to measure latitude gradients in the solar wind properties, the magnetic field and galactic and anomalous cosmic rays. Such information should improve our understanding of the solar wind's origins and possibly of the heating of the corona. Measurement of the magnetic field in the polar regions and it's characterization, including the extent to which the field is concentrated near the magnetic poles, also supports these goals. The intensity of galactic cosmic rays in the polar regions should determine the extent to which they can enter the heliosphere by means of a polar "funnel". Other objectives have included the effect of latitude on energetic particle acceleration, the three dimensional distribution of cosmic dust, and the processes involved in the ionization, pickup and acceleration of ions of interstellar origin. Ulysses was expected to characterize waves involving electric and magnetic fields and to investigate their role in collisionless plasma processes. Such waves cover an extremely broad range of frequencies from below those at which solar wind ions gyrate around the magnetic field (hydromagnetic waves), through and above the electron resonant frequencies (plasma waves), and into the radio frequency regime.

The scientific highlights of this first initial polar pass include the following (see figure 4, a diagrammatic summary). The solar wind (4) was found to increase in speed from the equator to the poles by a factor of about two, i.e., from -400 to -750 km/sec. Up to a latitude of -30° (approximately the tilt angle of the sun's magnetic dipole), large variations in speed were seen each solar rotation (a period of - 26 days). Ulysses alternately encountered slow solar wind from near the sun's magnetic equator and high speed solar wind from near the sun's south magnetic pole. Above ~50° latitude the solar wind speed became nearly constant. The high speed wind was presumably coming from a coronal hole covering the south polar cap. The speed neither increased further toward the pole nor reached a maximum at an intermediate latitude as some models had predicted.

The heavy ion composition of the slow (low latitude) and fast (high latitude) solar wind has been found to be markedly different with sharp compositional boundaries between the two types of flow (5). The relative abundances of magnesium and oxygen have been studied because magnesium can be ionized relatively easily whereas oxygen is more difficult to ionize. The Mg/O ratio changes abruptly between slow and fast streams, being higher in the slow streams. Neither abundance ratio is what would be expected for ions formed in the very hot corona but tend to be representative of values found below the corona in the lower temperature chromosphere. Neither the composition boundary nor the apparent influence of chromospheric processes was anticipated prior to Ulysses.

Measurements of the radial component of the magnetic field, which is most easily related to the global solar magnetic field have failed to show a latitude gradient (6). The field strength is the same in the polar regions as at the equator as is evident by comparison with simultaneous measurements being made in the ecliptic. Since remote sensing solar measurements reveal a well-developed dipole-like magnetic field, as expected near sunspot minimum, the Ulysses observations imply that excess magnetic flux from the poles is being re-distributed or moved equatorial d to yield a uniform field over a spherical surface between the sun and Ulysses. It has been customary to relate the solar and heliospheric fields through use of a "solar wind source surface" typically located at 2 to 3 solar radii beyond which the flow is assumed to be radial (7). The models used in the past, which have ignored magnetic stresses within the spherical shell between the sun and the source surface, will have to be re-examined in light of the Ulysses results.

The absence of a significant gradient in the cosmic ray intensity has also been a surprise (8). Prior to Ulysses, it was anticipated that the flux of cosmic rays would be much greater in the polar regions than near the ecliptic, In the polar caps, the radial magnetic field and the absence of the strong spiraling of the field introduced at lower latitudes by the sun's rotation were expected to allow easier access of the cosmic rays to the heliosphere. However, the Ulysses cosmic ray observations show only a slight increase from the equator to the poles.

Large amplitude, long period magnetic waves have been found to be continuously present within the polar coronal hole flow. The waves, which cause the direction of the field to vary continuously through large angles, were first noticed above -50° latitude and have been present throughout the high latitude pass. They consist of irregular waveforms covering a broad band of frequencies or wavelengths and constitute a form of turbulence. Correlations between the simultaneous variations in the magnetic field and solar wind velocity show that they are Alfven waves propagating outward from the sun. The longest wavelengths are comparable to the radii of gyration of the relativistic cosmic ray nuclei and should interact strongly with these particles reflecting them back into the outer heliosphere. Thus, the waves are thought to be impedi ng entry of the cosmic rays into the polar region. The origin of the waves and their effect on the solar wind and galactic cosmic rays have now become scientific issues of importance.

These and other results reported in the accompanying articles are causing a revision in many of our preconceived ideas regarding the solar wind and the heliosphere. An important qualification is that these initial observations have been obtained near sunspot minimum when the sun is in a particularly simple state. It will also be important to compare the present observations with those obtained next summer when Ulysses passes over the sun's north polar regions. Will the two hemispheres prove to be symmetric?

In the intervening interval, Ulysses will pass through perihelion at 1.34 AU and, as the spacecraft approaches the sun, will gain speed. The latitude gradients in all the important physical parameters will once again be surveyed, this time over a much shorter time interval which will help discriminate against time variations which might masquerade as spatial variations. Between November and June, an interval of 227 days, latitudes from -70° to +70° will be scanned rapidly.

After the spacecraft descends to 70° North on 2.9 September 1995, it will once again head out toward the orbit of Jupiter at 5.3 A.U.. By good fortune, the orbital period of Ulysses is 6.3 years so that, on the next revolution around the sun, the spacecraft will pass over the south and north polar regions during the coming solar maximum in 2,001-2002. Thus, continuation of the mission into the next century is expected to provide another unprecedented view of the sun when it and the heliosphere are in physical states very unlike present conditions.

## REFERENCES AND NOTES


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**TABLE I**

| investigation | Acronym | Principal Investigator | Measurement |
|---|---|---|---|
| Magnetic Field | VHM/FGM | A. Balogh, Imperial College, London (UK) | spatial and temporal variations of the heliospheric magnetic field: 0.01 to 44000 nT |
| Solar wind plasma | **SWOOPS** | J.L. Philips, Los Alamos National Lab (USA) | solar wind ions: 260 eV/q to 35 keV/q; solar wind electrons; 0.8 to 860 eV |
| Solar wind ion composition | SWICS | J. Geiss, Univ. of Bern (CH) G. Gloeckler, Univ. of Maryland (USA) | elemental & ionic-charge composition, temp. and mean speed of solar wind ions; 145 km/s ($H^+$) to 1350 km/s ($Fe^{+8}$) |
| Radio and plasma waves | URAP | R.G. Stone, NASA/GSFC (USA) | plasma waves, solar radio bursts, electron density, electric field plasma waves: 0-60kHz; radio: 1 -940kHz; magnetic: 10-500117, |
| Energetic particles and interstellar neutral gas | EPAC/GAS | E. Keppler, MPAe, Lindau (D) | energetic ion composition; 80kcV-15 MeV/n neutral helium atoms |
| Low-energy ions and electrons | HI-SCALE | L.J. Lanzerotti, AT&T Bell Labs, New Jersey (USA) | energetic ions; 50 keV-5 MeV energetic electrons; 30-3(X) keV |
| Cosmic rays and solar particles | COSPIN | J.A. Simpson, Univ. of Chicago (USA) | cosmic rays and energetic particles ions: 0.3-60 MeV/n electrons: 4-2(HIO McV |
| Solar X-rays and cosmic gamma-ray bursts | GRB | K. Hurley, UC Berkeley (USA) M. Sommer, MPE, Garching (D) | solar flare X-rays and cosmic gamma-ray bursts 15-150 keV |
| Cosmic dust | DUST | E. Grun, MPK, Heidelberg (D) | dust particles: $10^{-16}$ to $10^{-7}$g |
| **Radio** Science | | | |
| Coronal sounding | SCE | M.K. Bird, Univ. of Bonn (D) | density, velocity and turbulence spectra in the solar corona and solar wind |
| Gravitational waves | GWE | B. Bertotti, Univ. of Pavia (1) | Doppler shifts in S/C radio signal due to gravitational waves |

TABLE II

| | |
|---|---|
| Interdisciplinary Studies | |
| Directional discontinuities | M. Schulz, Lockheed Palo Alto Res. Lab. (USA) |
| Mass Loss and ion composition | G. Noci, Univ. of Florence (1) |
| Solar wind outflow | A. Barnes, Ames Res. Center (USA) |
| cornets | J.C. Brandt, Univ. of Colorado (USA) |
| Shocks | C.P. Sonett, Univ. of Arizona (USA) |

Figure Captions

1. Ulysses Trajectory

The flight path of Ulysses from launch to the end of the prime mission is shown. The scientific requirements imposed on the trajectory design were to spend as much time as possible above 70” latitude and to achieve the highest possible latitude. The spacecraft will continue to follow the highly inclined ellipse for at least the next several hundred years.

2. Ulysses Radial Distance and Heliographic Latitude While in the Polar Regions

The radial distance is given in Astronomical Units, The maximum heliographic latitude is >80°. The polar cap is defined as the region above 70” latitude.

3. Ulysses Spacecraft

This drawing shows the main features of the spacecraft which spins about the centerline of the fixed high gain antenna. It carries a full complement of particle and field experiments.

4. Representative scientific highlights of the. Ulysses south polar pass. The Sun and its relevant atmospheric regions are shown. The arrows represent the outflowing solar wind. The wavy lines are magnetic fields from the polar caps that are being transported equatorward and that are highly variable in direction because of the presence of waves. The dots represent cosmic ray particles that are gyrating about the magnetic field and being reflected back out into the heliosphere.

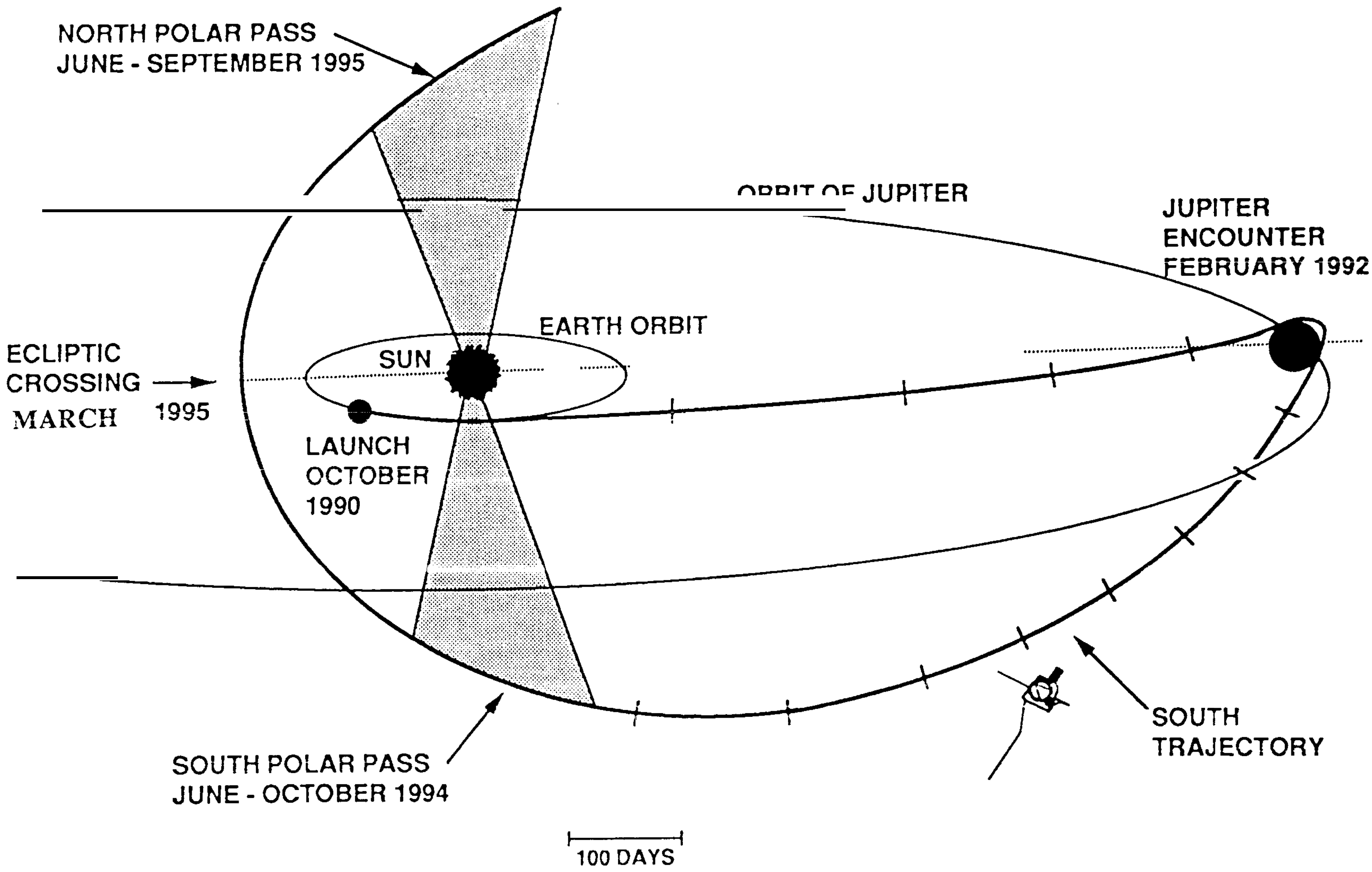
NORTH POLAR PASS
JUNE - SEPTEMBER 1995
ORBIT OF JUPITER
JUPITER
ENCOUNTER
FEBRUARY 1992
EARTH ORBIT
SUN
ECLIPTIC
CROSSING
MARCH
1995
LAUNCH
OCTOBER
1990
SOUTH POLAR PASS
JUNE - OCTOBER 1994
SOUTH
TRAJECTORY
100 DAYS

Figure 1

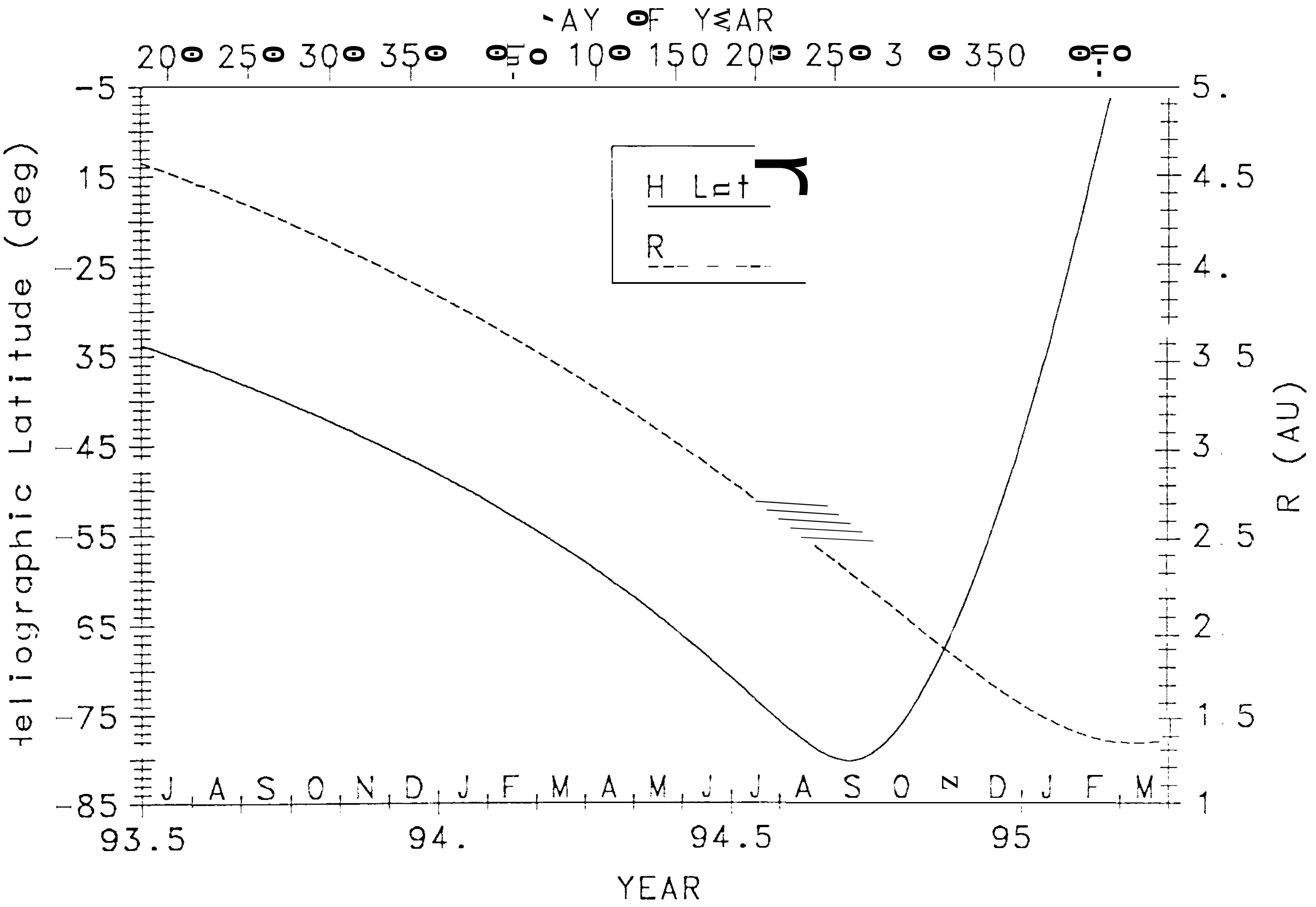
DAY OF YEAR
200 250 300 350 0 50 100 150 200 250 300 350 0
Heliographic Latitude (deg)
-5
-15
-25
-35
-45
-55
-65
-75
-85
R (AU)
5.
4.5
4.
3.5
3.
2.5
2.
1.5
1
H Lat
R
J A S O N D J F M A M J J A S O N D J F M
93.5
94.
94.5
95
YEAR

Figure 2

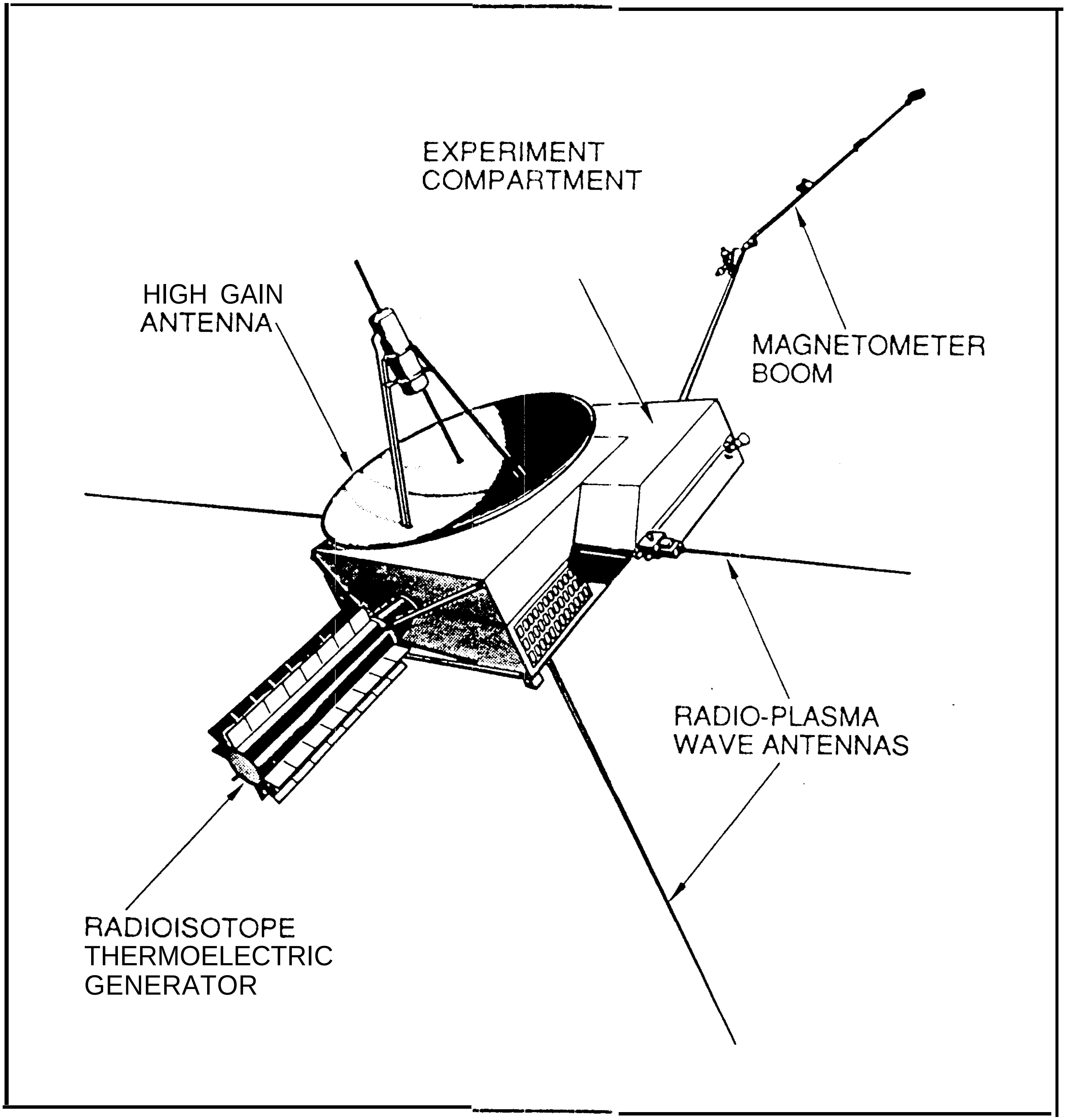
EXPERIMENT
COMPARTMENT
HIGH GAIN
ANTENNA
MAGNETOMETER
BOOM
RADIO-PLASMA
WAVE ANTENNAS
RADIOISOTOPE
THERMOELECTRIC
GENERATOR

Figure 3

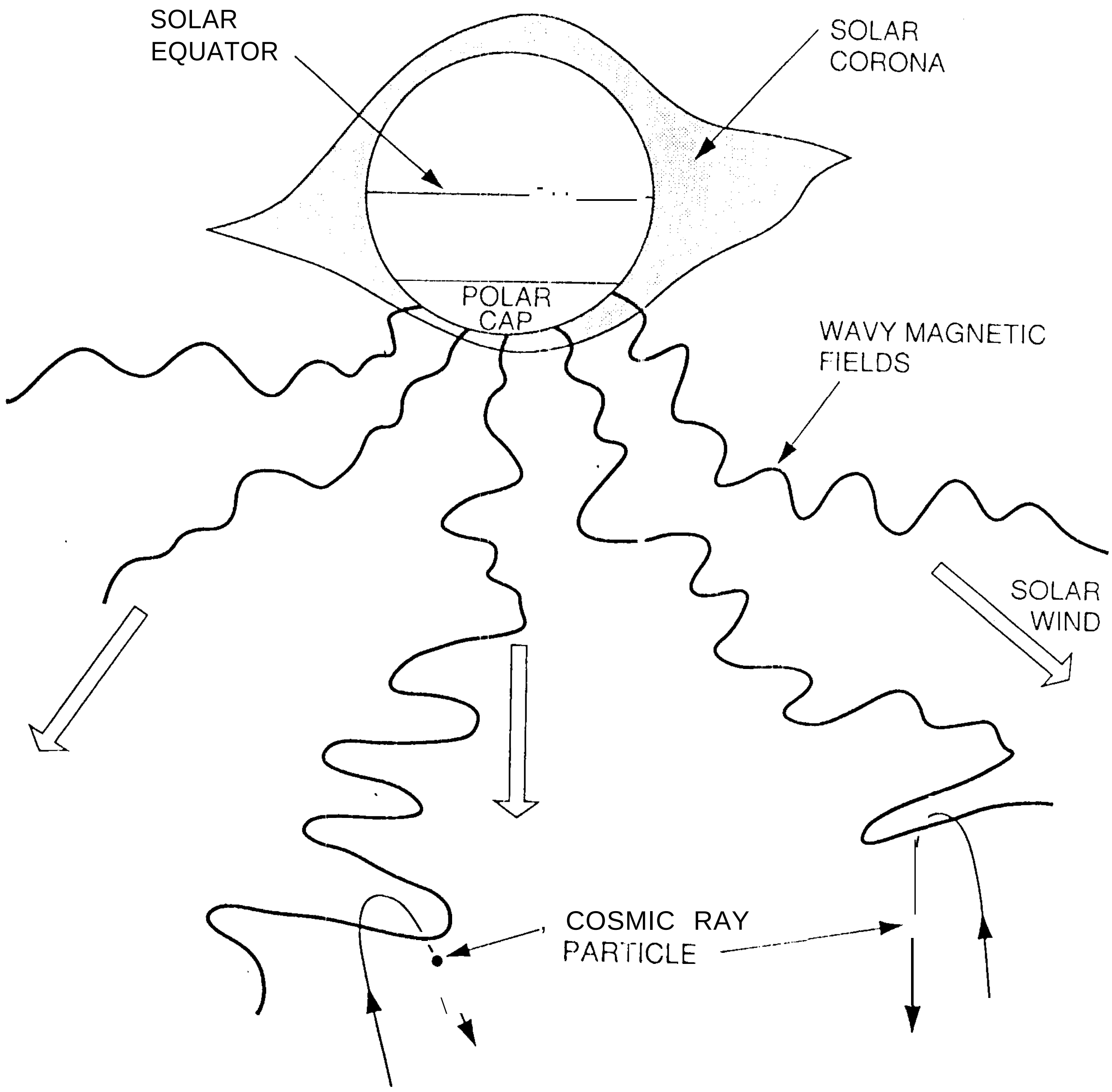
SOLAR
EQUATOR
SOLAR
CORONA
POLAR
CAP
WAVY MAGNETIC
FIELDS
SOLAR
WIND
COSMIC RAY
PARTICLE

Figure 4